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Determining the phase of the diurnal, solar thermal tidal wave in the upper atmosphere using nighttime Na lidar measurements

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Solar thermal tidal waves play a critical role in the dynamics of the mesosphere and thermosphere. Obtaining measurements of the diurnal tidal wave above 100 km is difficult. This could be solved using a physics-based empirical model. To derive this model requires knowing the phase at different points along the tidal wave. In this study, I determine the phase at multiple points along the thermal diurnal tidal wave using measurements taken by a fluorescence lidar in the range of 80 to 100 km. A simple calculation of the phase based on the zeroes and extrema of the wave is demonstrated.

I. INTRODUCTION

The atmosphere experiences tides in temperature, wind, density, and pressure which are generated by the sun and moon.[1] The largest of these tides are forced waves caused by periodic heating from the sun. The diurnal cycle of the sun causes the atmosphere to experience heating during the day and not at night, causing these tides to be global-scale waves with periods related to the solar day. These waves have periods of 24, 12, 8, and 6 hours. It has been observed that the tides with the largest amplitudes have periods of 24 and 12 hours, referred to as diurnal and semidiurnal tides, respectively.[1]

The 24 and 12 hour solar thermal tidal waves play a key role in the dynamics and chemistry of the mesosphere and thermosphere.[1,2] It is difficult, however, to make ground based tidal wave measurements above 100 km[3], especially for the temperature component of the diurnal tidal wave. These measurements are important for observing the coupling between the mesosphere and thermosphere regions.[3] A proposed solution to this is to create a physics-based empirical fit model using observations at lower altitudes in the upper mesosphere and lower thermosphere.[4,5] One of the key pieces needed to create an empirical model like this is the ability to find the phase of the wave at different altitudes.

As previously mentioned, the diurnal and semidiurnal tidal waves have the largest amplitudes, so when trying to find the phase, it is assumed that the waves with periods of 8 and 6 hours have a negligible effect on the overall wave structure. The semidiurnal wave, however, will have a non-negligible effect when working with the diurnal wave modulation. To combat this, the difference of measurements that are taken 12 hours apart are used so as to cancel out the effect of this 12 hour wave modulation. The purpose of this paper is to apply this methodology to measurements taken by a Na lidar.

II. MEASUREMENTS

The Utah State University (USU) Na lidar[6] has been operating in Logan, Utah (41°N, 111°W) since the summer of 2010. It is a fluorescence Doppler lidar that is tuned to the sodium D2 line and is primarily set up to take nighttime measurements in the north, east, and west directions simultaneously. It is designed to measure neutral temperature and wind profiles in the mesopause region, which is from about 80 to 110 km. The lidar operates year-round when the weather conditions are favorable, meaning no precipitation and little to no cloud covering.

To make use of nighttime measurements for this study, it is necessary to use data taken during the winter when the nights are long enough to capture measurements which are 12 hours apart. A limiting factor when taking winter measurements is the frequently poor weather conditions that can limit the ability to perform lidar observations, especially over consecutive nights. These factors limit the total number of usable observations to a relatively small amount compared to the total number of observations.

III. METHODOLOGY

Temperature measurements were subtracted from measurements captured 12 hours later so as to eliminate the influence of the semidiurnal tide and leave a profile primarily of the diurnal tidal that is being investigated. This profile should look akin to a simple harmonic wave, like in Fig 1.

When there is sufficient data collected over multiple days, it is beneficial to average the measurements at each time over the consecutive days. The diurnal tidal oscillation is a fairly stable structure, so the measurements performed at each 24 hour interval should be quite similar. By averaging them, random variations in the measurements can be reduced.

The goal is to find the phase at different points along this structure. To do this it is necessary to find the altitudes at which the zero points and the local extrema occur. Discrete data sets were used, so to find the exact points where the temperature difference is zero, a Python[7] library called PyAstronomy[8] was used to perform a linear interpolation of consecutive data points showing a change in sign. These points can be seen in Fig. 1, denoted in black.

The next points needed are the relative maximums and minimums. Two different methods were used to find these. The first method is simply to use the maximum or minimum points in the data set. This works reasonably well for data sets that appear to have only a single wave structure. This however, is

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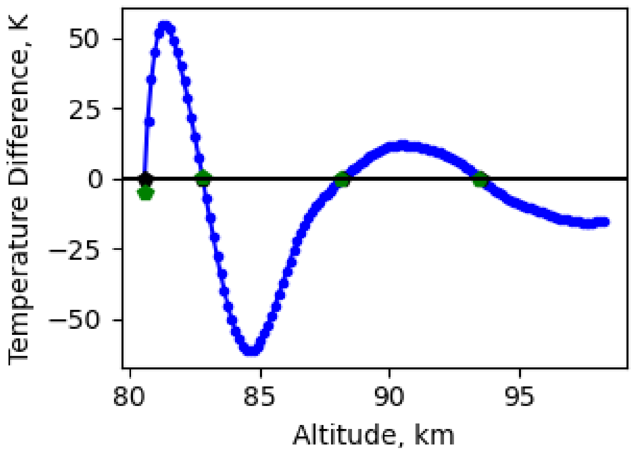

FIG. 1. Data points from data taken in 2010 on October 14th at 8:30 UTC subtracted by data from the 13th at 20:30 UTC. The black points are where the x-axis is crossed and green points are the data points prior to the crossing.

not always the case. Other oscillations in the data can lead to no relative extrema where expected, like in Fig. 2. The second method, which is used to remedy this, is to perform a linear interpolation based on the points near the zero crossings, then use their intersection to get a rough estimate of the altitude where the maximum or minimum should occur.

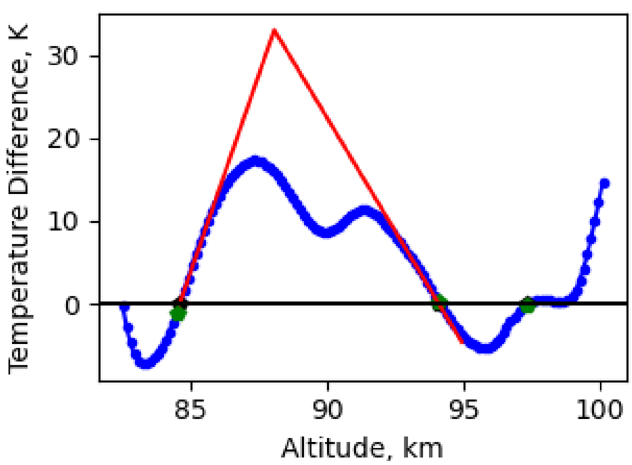

FIG. 2. Data points from data averaged over the 9th, 10th, and 11th of November in 2011. Data averaged at time 1:30 UTC each day is subtracted from data averaged at 13:30 UTC each day. There is interference occurring with the overall wave structure, causing there to be no local maximum where expected. The red lines represent linear interpolations based off of the points near the zero crossing. The altitude at which their intersection occurs is used as the location for the local maximum.

The same method was attempted on data sets without this issue, but minor variations in slope near the zero points led to

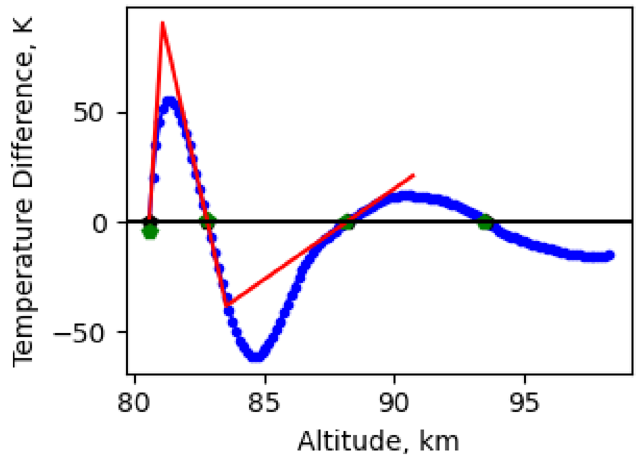

FIG. 3. Same data as Fig. 1 but with red lines that represent an attempt to use linear interpolation to find relative extrema. Using this method clearly does not work for the minimum in this case, estimating the minimum to be far above many other points due. This is a result of the shallow slope at one of the crossings.

estimations with a large discrepancy from what was expected, which can be seen in Fig. 3. The usability of this method seems limited due to this. A potential way to make this more effective is to base the interpolations off of more data points, but it is difficult to choose a useful cutoff. In the discrepancy seen in Fig. 3, taking more data points from the immediate left or right of the zero crossing does not help in reducing this discrepancy.

Now that the zero points and extrema have been found, the phase for each of these points can be calculated using the equation

$$T(z) = A(z)\cos(\omega t + \phi(z)), \tag{1}$$

where T is the temperature difference, $A(z)$ is the amplitude as a function of height, ω is the angular frequency, t is the time, and $\phi(z)$ is the phase as a function of height.

For the zero points, $T(z) = 0$, so ϕ can be solved for using a simplified Eq. (1):

$$\phi(z) = \omega t - \frac{\pi}{2}. \tag{2}$$

For the extrema, $T(z)/A(z) = \pm 1$, where the sign depends on whether it is a maximum or minimum. Using this result in Eq. (1) then simplifying gives

$$\phi(z) = \omega t. \tag{3}$$

Now only values for ω and t are needed. Deriving ω is simple as it can be found by using

$$\omega = \frac{2\pi}{T}, \tag{4}$$

where T is the period of the wave, which is known to be 24 hours for the diurnal tidal wave. This gives the result $\omega =$

$\pi/12$. The value used for t isn't quite as simple because data from two different times are being used. I chose the value of t to be the average of the two times used. As an example, for Fig. 1 where the times are 20:30 and 8:30, t is 2.5, or 2:30.

IV. RESULTS

The first data set used is that shown in Fig. 1. With this data I am able to directly find the extrema without using an interpolation. The points used and their corresponding phases are given in Table I.

TABLE I. Results for data in Fig. 1. Data points from data taken in 2010 on October 14th at 8:30 UTC subtracted by data from the 13th at 20:30 UTC. The altitude of each point is given by z and the values are ordered from least to greatest. The extrema are found directly from the data points.

z (km)	Point Type	$\phi(z)$
80.6	zero	$-7\pi/24$
81.4	maximum	$5\pi/24$
82.8	zero	$-7\pi/24$
84.6	minimum	$5\pi/24$
88.2	zero	$-7\pi/24$
90.6	maximum	$5\pi/24$
93.5	zero	$-7\pi/24$

The second set of data used can be seen in Fig. 2. For this set the interpolation method for finding extrema is used. This data set is also an average taken over multiple days, making it a more reliable representation of the diurnal tidal wave as opposed to using the data from a single day. The results are summarized in Table II.

TABLE II. Results for data in Fig. 2. Data points from data averaged over the 9th, 10th, and 11th of November in 2011. Data averaged at 1:30 UTC each day is subtracted from data averaged at 13:30 UTC each day. The altitude of each point is given by z and the values are ordered from least to greatest. The maximum is found by finding the intersection of two linear interpolations performed at each zero crossing between the maximum.

z (km)	Point Type	$\phi(z)$
83.2	minimum	$5\pi/8$
84.6	zero	$\pi/8$
88.1	maximum	$5\pi/8$
94.1	zero	$\pi/8$
95.8	minimum	$5\pi/8$
97.4	zero	$\pi/8$

In this study I estimate the accuracy of the lidar to be about $\pm 1K$. It is difficult to determine the accuracy of the results for the phase without further developing an empirical fit model for the diurnal tidal wave. I expect the altitudes at which the zeroes occur to be more accurate than the extrema, especially when interpolation is used for the extrema.

V. CONCLUSION

In this report, I have developed a simple method for isolating and determining the zeroes and extrema of the diurnal tidal wave and the phase at each of these points. I have shown an approach for data sets that have a clear wave structure as well as those that may have other waves causing small amounts interference like in Fig. 2.

The results demonstrate that measurements taken from a Na lidar ranging from 80 to 100 km can be analyzed to help create a physics-based empirical fit model, which could be used to better understand the effect of the diurnal tide at heights above 100 km. Further development of this model will help show if the results from this study are reliable for understanding the thermal diurnal tidal wave.

Finding a viable data set to apply this method to presents a challenge. It is limited to winter-time observations in which there are nighttime measurements available at a 12 hour interval. While it is preferred to average the data over multiple consecutive days, this data is seldom attainable due to weather conditions. A solution to this could be using data from a lidar system that is able to run continuously for 24 hours.

Interference from other waves can make it difficult to analyze the usable data if that interference proves to be too much for the interpolation method to handle. This attests to the complexity of understanding this region of the atmosphere and how the diurnal tide plays a large role in its dynamics.

ACKNOWLEDGMENTS

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